Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 1 December 2020 doi:10.20944/preprints202012.0006.v1

Article

Knud Rasmussen Glacier Status Analysis Based on Historical Data and Moving Detection Using RPAS

Karel Pavelka [1], Jaroslav Šedina [1], Karel Pavelka jr.

[1] Czech Technical University in Prague, Faculty of Civil Engineering, Thakurova 7, Czech Republic; pavelka@fsv.cvut.cz, Jaroslav.sedina@gmail.com, karel.pavelka@hotmail.com

* Correspondence: pavelka@fsv.cvut.cz; Tel.: +420-608211360 (KP)

Abstract: This article discusses an international scientific expedition to Greenland that researched geography, geodesy, botany, and glaciology of the area. The results here focus on the geodetic and glaciological results obtained with the eBee drone in the eastern part of Greenland at the front of the Knud Rasmussen glacier. From two overflights nearby the glacier front, it was possible to obtain the speed of the glacier flow and the distribution of velocities in the glacier stream. The results correlate with other measurement methods and this technology has been shown as feasible. Of course, there are more accurate and long-term options or devices for monitoring the flow of glaciers. In this case of short-term visits to the site, the possibility of using a drone is interesting and the results show not only the flow speed of the glacier, but also the shape and structure from a height of up to 200m. The second part of the paper focuses on the analysis of modern satellite images of the Knud Rasmussen glacier from Google Earth (Landsat series 1984-2016) and a comparison with historical aerial images from 1932-1933. Experimentally, historical images were processed photogrammetrically into a 3D model.

Keywords: Greenland; photogrammetry; Knud Rasmussen Glacier; RPAS;

1. Introduction

1.1. Dedication

I would like to dedicate this article in memoriam to my friend, scientist, and real man, Professor Wilfried Korth (Fig.1.), who tragically died in the spring 2019, just before his last planned expedition to Greenland (KP).

Figure 1. Professor Wilfried Korth († 2019).

1.2. Arctic research

Arctic research has been a matter of hundreds of years [1]. Cruises to the north are dated to the 16th century. In addition to the scientific goals of the expeditions, there were also prestigious expeditions, which aimed to reach the North Pole of our planet.

There is still controversy over who stood as a first one at the North Pole; it is generally claimed that Frederick Cook was the first in 1908, but he could not credibly prove his primacy. Furthermore, the North Pole was reached in 1909 by Edwin Peary, accompanied by a servant Matthew Henson

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 1 December 2020 doi:10.20944/preprints202012.0006.v1

and four Innuits; there is also controversy over his triumph, as well as the first overflight of the North Pole by Richard Byrd and Floyd Bennett in a plane in 1926. The first truly documented achievement of the North Pole was with Norge airship in 1926, onboard with Roald Amundsen, Italian airship designer Umberto Nobile, and Lincoln Ellsworth [2]. In 1928, on the return from the North Pole, the airship Italia with Commander Umberto Nobile crashed. The Czech scientist František Běhounek was also a member of the crew [3], and survived the expedition; part of the team was saved later by the Soviet icebreaker Krasin. Unfortunately, the polar explorer Roald Ammundsen, the pilot and crew died in the rescue operation.

This article deals with the research of Greenland. Greenland was discovered after 982 by the Viking Erik the Red. Thanks to the warmer climate, the Vikings lived there until the middle (maybe till the end) of the 14th century, when a global cooling started. Until the 18th century, only Inuit people who migrated from North America lived there, later Europeans and Americans began to infiltrate Greenland and established trade settlements. Since the beginning of the 19th century, Greenland has been a part of Denmark, and since 1979 it has had extensive autonomy with its own parliament. Due to the gradual warming and melting of the Greenland Glacier, Greenland has great potential for the future thanks to its large reserves of mineral wealth. However, the melting of the Greenland Glacier can have fatal consequences for the whole world [4] .

Since the 1980s, ice has been declining more than it is recreated in winter. Winters are milder and summers longer and warmer. The ice that disappears will not be restored. Nowadays, six times more ice has been disappearing from Greenland than in the 1980s [5].

The Greenland Glacier is a vast mass of ice covering 1.7 million square kilometres, which represents about 80% of Greenland's surface. It is the second largest glaciated area in the world, first is the Antarctic glacier. Its thickness is usually more than 2 kilometres and sometimes exceeds 3 kilometres [6] . The weight of the glacier has compressed the central part of Greenland, bringing the rocky bedrock below it to about sea level, while the mountain range surrounds the glacier almost along its entire edge. This is detectable by the deformation of the Earth's gravity field. If the entire Greenland Glacier melted, the level of the world's oceans would rise by about 7 meters. Due to the long-term melting of the glacier, the compressed rock is gradually rising on the outskirts of Greenland. According to the scientific studies, the Greenland coast rises by 2.5 cm per year [7,8]. However, it is also scientifically confirmed that some parts of the glacier are even increasing . This information indicates that the condition of the Greenland Glacier must continue to be carefully studied. Today, scientific satellites in particular are contributing to this [9] .

Greenland's scientific research is linked to the significant deeds of travellers, ethnography and polar explorers.

One of the first researchers in Greenland was undoubtedly the legendary Fridtjof Nansen (1861-1930). In 1888, he crossed with the six-member group as the first one Greenland´s glacier in the length of about 650 km. He proved that it is covered with ice from the entire interior of Greenland, and obtained a unique set of meteorological measurements. Due to the extreme weather, they spent the winter with the Inuit and could return home an year later [10].

Knud Rasmussen (1879-1933) was one of the first and one of the most important polar researchers and ethnographers in Arctic (Fig.2.). He was born in Jakobshavn (Illulisat) into the family of a Danish missionary. He was engaged in ethnography and used a dog sled to travel around a large part of Greenland. During the first of seven expeditions to the north part of Greenland, he founded, among other things, the Thule trading station [11].

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 1 December 2020 doi:10.20944/preprints202012.0006.v1

Figure 2. Knud Rasmussen.

In 1912 Alfred de Quervain undertook an important scientific Swiss Greenland Expedition, during which meteorological and geodetic information was measured. He and his team crossed the Greenland Glacier in a north-westerly direction for almost 700 km [12]. It is interesting, that one member of the team was Roderich Fick, the grandfather of Stephan Orth, the participant in a German expedition to the centenary of the expedition of Alfred de Quervain led by Professor Wilfried Korth in 2012 [13], (Fig.3.).

Figure 3. Map of Greenland and the Knud Rasmussen Glacier. (http://www.getamap.net/maps/greenland_%5B_denmark_%5D/ostgronland/_knud_rasmussen_glacier/)

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 1 December 2020 doi:10.20944/preprints202012.0006.v1

The mapping of Greenland began as early as the 15th century when parts of the coast were mapped. However, systematic mapping was possible only in the 20th century using aerial photogrammetry and later from satellites. A significant achievement was the Danish geodetic expedition in 1931-34. Many aerial photographs were taken using three Heinkel seaplanes. These photographs are perfect source for monitoring the condition of Greenlandic glaciers (Fig.4.).

During the seventh Thule Expedition a systematic survey of the southeast coast of Greenland was carried out in 1932–1933. Aerial photographs of the Knud Rasmusen glacier were taken in this time. Nowadays, at the Natural History Museum of Denmark, there is a long-term project called „AirBase ". It is a database which has a quarter millions of aerial photos recorded by Danish survey agencies in the period 1930 to the 1980s. This is a unique source of information about glaciers [14, 15].

Figure 4. The Knud Rasmussen Glacier in a photo from the Danish Greenland expedition (the seventh Thule Expedition 1932-33); (photo The Arctic Institute, https://arktiskinstitut.dk/).

2. University research

The Department of Geomatics, Czech Technical University in Prague, Faculty of Civil Engineering, has focused on the documentation of historical monuments and landscape using photogrammetry for a long time, more recently also using laser scanning and geophysical methods [16,17].

In 2014, cooperation was established between the Beuth Hochschule für Technik Berlin, TU Cottbus, and the Czech Technical University in Prague, Faculty of Civil Engineering. This was based on contacts between a prominent German polar explorer and surveyor, Professor W. Korth, and Professor K. Pavelka, a specialist in remote sensing and photogrammetry.

After consultations and training in Norway, a joint expedition to Greenland was organized in 2015. A German group led by Professor W. Korth made research in Greenland since 2002 and crossed the 700 km long Greenland Glacier using skis five times in the footsteps of the Swiss polar explorer Alfred de Quervain. The aim was to measure the profile of the glacier using GNSS equipment and complementary meteorological and glaciological information.

The expedition in 2015 consisted of two teams. The first expeditionary team went from the east coast through Greenland to the west, a small support team met the first one at a place called Swiss Camp, about 100km from the west coast on a glacier. Both groups then went further to the ice border, where further experiments were performed. It involved the placement of four radar reflectors to monitor the movement of the glacier using the Terra SAR X satellite, as well as the detection of the movement of the Egi Glacier in Disko Bay using a winged drone. These researches were designed and performed by professor Pavelka from CTU FCE, Prague. The results were applicable and published [18]. The use of a drone proved to be possible and suitable despite the extreme conditions, the impossibility of supporting measurements of control points, and difficult and inaccessible terrain.

Following the success of the 2015 expedition, a new expedition with a similar composition was planned for 2019. Sailing with a research ship along the east coast of Greenland was planned and a new crossing over the Greenland Glacier in the same route as during the previous expeditions. By repeating the crossings along the same route and measuring, interesting information should have been obtained about the decrease in ice and climate change.

In spring 2019, unfortunately, Professor W. Korth died tragically. After discussions, the already prepared expedition took place, but with a minimal team and without crossing the Greenland Glacier. All that remained was a research ship sailing around a part of the east coast to the famous glaciers near the Kulusuk village and a shorter research voyage to the glacier.

2.1. Cruise and planned research

The research ship voyage was arranged for me without much information as only Professor W. Korth had the details. After arriving in Kulusuk from Reykjavik (Island), it was necessary to wait for the ship. The situation became complicated because of the weather, the plane did not fly, and I (KP) remained alone from the three-member team on the island with minimal equipment, but with a computer and a disassembled drone. It was necessary to spend some nights with the locals who helped me. Third day, the expedition sailing vessel Dagmar Aaen arrived with the crew and captain Arved Fuchs, a world-famous traveller and researcher. It was a surprise for me, I had no information about it, only an email communication, and a link to Wilfried Korth. Dagmar Aaen is formerly a fishing cutter built in 1931 and adapted by Arved Fuchs to a research expedition ship, which has already made several research voyages to the Arctic. After a short voyage, we picked up a late participant in the expedition, a student Luisa Näke, who participated in the expedition within the Erasmus program and for the future final bachelor's thesis [19], (Fig.5).

Figure 5. A research ship sailed around a part of the east coast to the famous glaciers (one week); this image was taken in in the navigation cabin.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 1 December 2020 doi:10.20944/preprints202012.0006.v1

Figure 6. Knud Rasmussen Glacier; it seems to be a small glacier, but its width is over 2km.

2.2. Planned research

The goal was to select sites within a few days of sailing from Kulusuk, such as researching an abandoned US military base from World War II Bluei East II. and research and measurement of the melting glaciers (Fig.6.). This research is a follow-up to a number of projects focused on the documentation of glaciers using drones and the detection of changes using point clouds [20, 21, 22].

The crew consisted of a professionally diverse team from the fields of biology, photogrammetry, reporters, students, and others.

Aim of the photogrammetry was to create detailed maps of Bluei East II. and drone research on the movement of glaciers. As the satellite images are out of date or unactual, it was not possible to precisely define the exact parameters and destination of the drone flight. As in 2015, this proved to be a problem. The front of the glacier was hundreds of meters away from the latest satellite images, so the flight plan had to be estimated (Fig. 7-8.).

2.3. Flights

RPAS (remotely piloted aircraft system) is a less used but correct acronym for a drone. It means that there is a pilot who remotely controls the device - and is therefore responsible for it. The eBee drone was used in this case for different reasons. 1) it is light, made from styrofoam, easy to use, takes off from the hand and lands without a special place, 2) it is easy to transport (in a padded backpack), it can be divided into several parts for transport, electrical powered, using small batteries, 3) it has a relatively long time of flight and altitude access (it is winged drone), 4) it flies fully autonomy and has changeable cameras.

One single day was set aside for the measurement, and there wasn't more time. The weather was favourable, which is an exception here. We (K. Pavelka and L. Näke) were transported by a small boat near the Knud Rasmussen glacier. When performing the flight and waiting for the next one, it was necessary to monitor not only the drone on the computer but also the surroundings; in

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 1 December 2020 doi:10.20944/preprints202012.0006.v1

case of a polar bear attack, we were equipped with a rifle. Fortunately, this did not happen. We were aware that in the event of a drone crashing or losing control, we would lose the drone. It was not possible to ascend the glacier, and the drone was moving at two kilometres. The landing site was too small on the coastal stone moraine, but fortunately, the drone was not damaged.

We had two changeable cameras at disposal for the drone. Due to a malfunction of the RGB camera, we used a NIR camera, which has a better passage of rays through the atmosphere and better imaging, and in the end, it was also more suitable for capturing ice than an RGB camera (glacier ice is off-white to light blue which is not perfect for image correlation used for image processing). Using the drone eBee, two overflights of the same area were performed with a time span of about 4 hours. During the first flight, a total of 162 NIR images were taken (Fig.8 b). During the second flight, 170 NIR images were recorded. During the first flight, a signal was lost due a very high rock cliff nearby by the last flight line; the drone emergency system interrupted the flight and returned it to the take-off point.

The flight time took approximately 35-40 minutes at an altitude of 180 m. Due to the smaller capacity of the batteries in the frost, we did not choose a lower flight or a longer flight. Another problem was the high rocks on both sides of the glacier.

The last flight line was not fully completed, it was not the time to repeat flight and therefore the second flight was slightly modified. The aim was to record both shores of the moraine, which could not change in a few hours, unlike the movement of the glacier, which was supposed to be the largest somewhere in the middle.

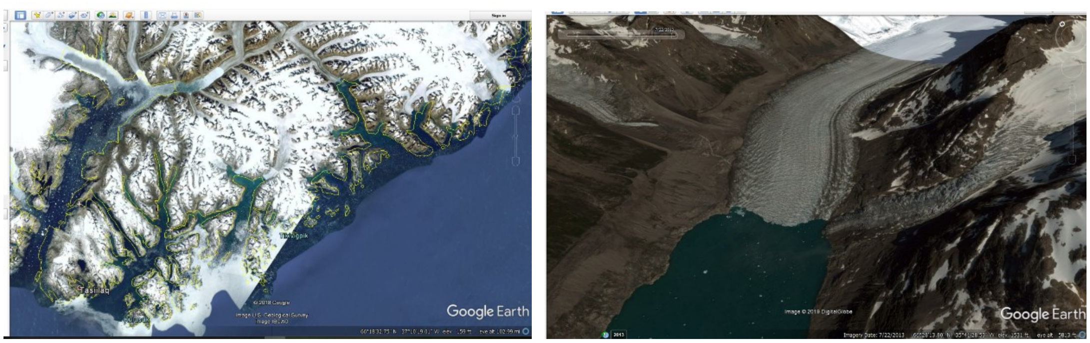
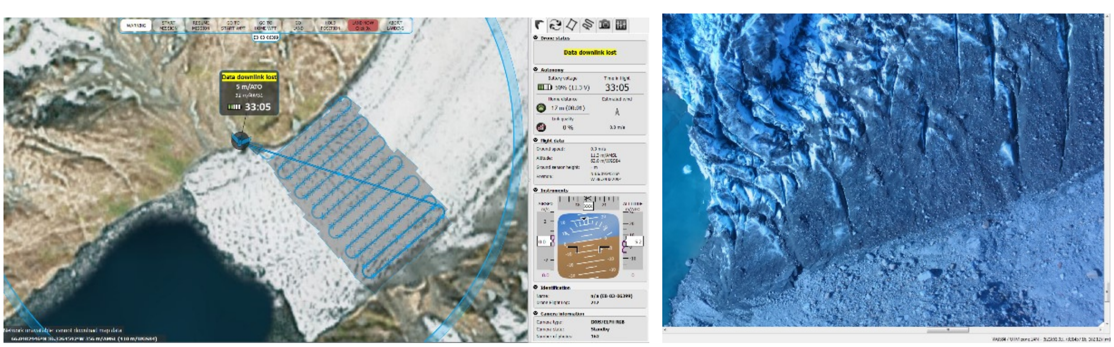


Figure 7. Google Earth - processed satellite images (but the latest is from 2016).



(a) (b)

Figure 8. (a) Flight No.1 (SenseFly eMotion 2; the map background was out of date and the flight plan had to be estimated), (b) a typical photo using NIR camera Canon PowerShot ELPH 110 HS (NIR).

2.4. Data processing

The data could only be processed in a laboratory at the University in Prague (not directly during the expedition).

Data processing was performed by Agisoft Metashape program. The Highest setting was used to orient the images. 74,416 tie points were found in the first set of images (sparse point cloud). In the second set of images, the number of connecting points was 92,693. After the depth map was created, 221,341,562 points (dense point cloud) were created for the flight and 231,635,556 for the second flight. Both point clouds were exported without modifying the coordinate systems.

Creating a point cloud, orthophoto, and DSM (digital surface model) was not a problem (Fig.9-10); the problem was to calculate the movement of the glacier in two flights, it moves nonlinearly (at the edges slowly and in the middle fastest). The difference in point clouds is usually calculated in CloudCompare software; in this case, it simply did not work due to nonlinear motion.

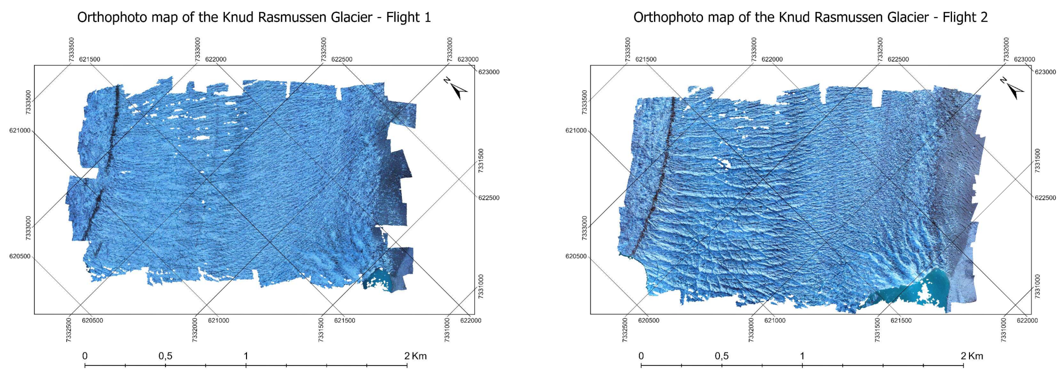


Figure 9. Flight No.1 and flight No.2 (orthophoto in near infrared range).

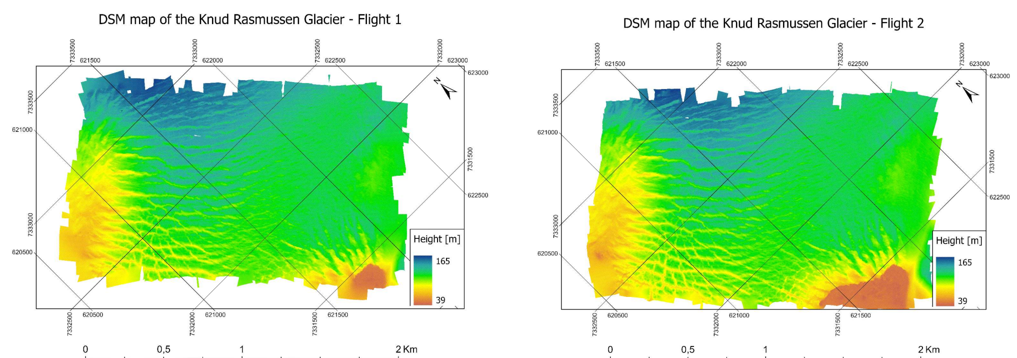


Figure 10. Flight No.1 and No.2 - DSM.

Accurately reference both point clouds from individual flights were a big problem. There were no control points; it would be impossible to place them on the glacier. GNSS equipment on the drone has an accuracy of 3-5m, which is not sufficient for this purpose. The assumption of movement in a few hours was one to several meters maximally. The RTK system was not available and it would not work here due to the short measurement time and conditions (no reference station was at disposal too).

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 1 December 2020 doi:10.20944/preprints202012.0006.v1

2.5 Joining of both point clouds

Experiments were conducted to connect both point clouds from two overflights to each other exactly. The first model was defined as a reference and the second was transformed into it. The problem occurred with joining of the second point cloud with the tie points detected at the edge of the model in a stone moraine. These found points were relatively stable and were used as fixed points.

However, based on the unstable and inaccurately determined elements of internal and external orientation (the drone has less than one kilogram and the flight is very affected by gusts of wind and further camera used are low cost), the second model was joined with the reference one at their edge excellent due to tie points, but in the middle, a model deformation has occurred and it reaches more than 2m.

The software performs by joining a new calculation using the tie points as the control points (points found on the first model, but only on edges of the model; in the middle of the glacier, considerable movement is expected here and it is not possible to define high-quality fixed tie points) and deforms the model by correcting the elements of external orientation during the new bundle adjustment process. The model curls.

It was necessary to use a different procedure. Models cannot be joined only at fixed points or control points at the edges of the model, because then an unknown deformation occurs in the middle of the model. Both models were calculated separately, and the second model was joined only by a similarity transformation (shifts, three rotations, scaling) using 6 tie points. It finally gave usable results with an RMS of 0.67m.

A similarity transformation in 3D was used (Equation 1.):

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} X_0 \\ Y_0 \\ Z_0 \end{pmatrix} + m.\mathbf{R}.\begin{pmatrix} x \\ y \\ z \end{pmatrix} \tag{1}$$

where (X,Y,Z) are the final coordinates in the system of first model, (Xo, Yo, Zo) are the shifts, m is the scale and (x,y,z) are the coordinates in second model.

The spatial seven-element transformation is given by seven unknowns, three translations, three rotations and one scaling. The affine spatial transformation is similar to the seven-element transformation, but it has nine unknowns, there are three scale values (there is a different scale for each axis). To calculate the transformation key, it is necessary to calculate approximate values and proceed this by iteration. However, in the case of incorrectly determined identical points, a problem with the convergence of the calculation occurs. Both types of transformation are programmed in Delphi, originally on the Faculty of Civil Engineering such as other university software for geodetical using [23].

m is a scalar (similarity transformation) or ***M*** is a matrix (affine transformation, Equation 2.)

$$\mathrm{M} = \begin{pmatrix} my & 0 & 0 \\ 0 & my & 0 \\ 0 & 0 & mz \end{pmatrix} \tag{2}$$

This result (RMS = 0.67m) is acceptable due to the pixel size of 10 cm and the type and structure of the surface, including possible actual deformation of the glacier over time. Better results cannot be expected under the current conditions and used equipment. It should be noted that the model was created from images taken in a time span of approximately 35 minutes. Even in this short time, parts of the glacier probably moved.

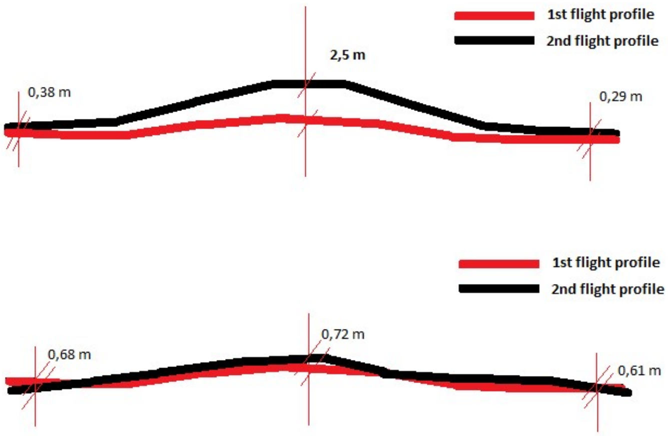


Figure 11. Schematic deformation of both models after joining the point clouds with tie points, found at the edge of the model in a stone moraine (it should be stable).

Subsequently, both point clouds were spatially joined in the CloudCompare program. A total of eight tie points (no exact control points measured with a precise GNSS devices were at disposal) were used for identification and the total RMS was 0.67 m (Fig.11-12).

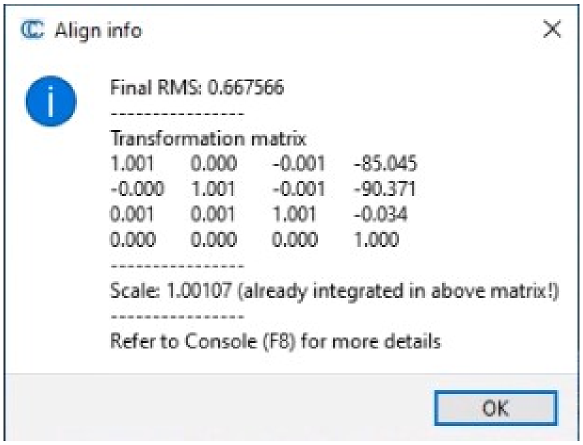


Figure 12. Final RMS for both point clouds joining.

3. Data analyse

The next part was the analysis of the joined models and the search for real shifts in time. A comparison of changes was performed using the Model-to-Model Cloud Comparison (M3C2) method [24], (Fig.13). This is a method of calculating the distance between two clouds. The method calculates distances only for so-called core points. This is the selection of a smaller sample of points from the whole reference point cloud (however, the whole cloud is used for the calculation).

The points are usually selected based on the minimum distance they must contain. In the first step, the normal vectors for each point are calculated. All points located at the maximum spherical distance (s) specified by the user from the core points are used to calculate the normals. If the clouds contain normal vectors from postprocessing, these normals can be used.

For each core point, a normal vector is calculated, which is the average of the normals of all points that lie from the core point with the maximum distances. This vector forms the axis of the cylinder. In the next step, a cylinder with a user-defined height (h) and radius (r) is interposed by a cloud. The core point forms the centre of this cylinder. The position of a point is calculated as the average of all points that are in this cylinder. A more detailed description of the method can be found in Lague. et al. (2013) [25, 26], (Fig.14-15).

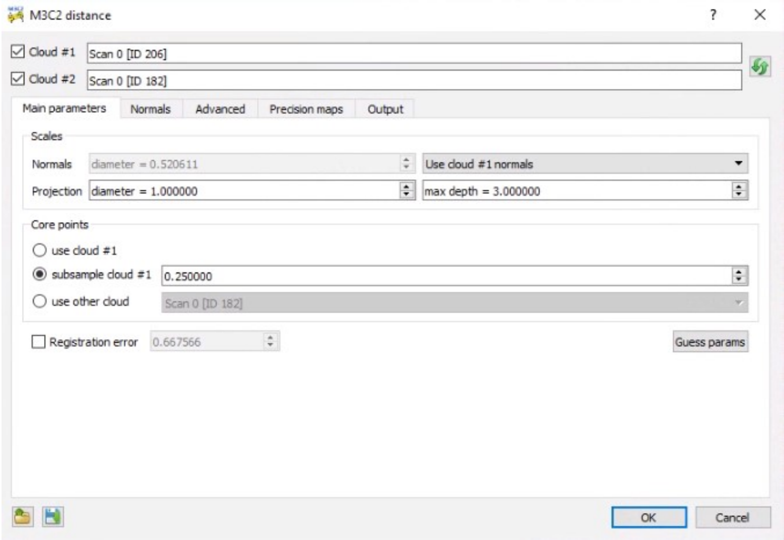


Figure 13. Model -to-Model Cloud Comparison (M3C2) method.

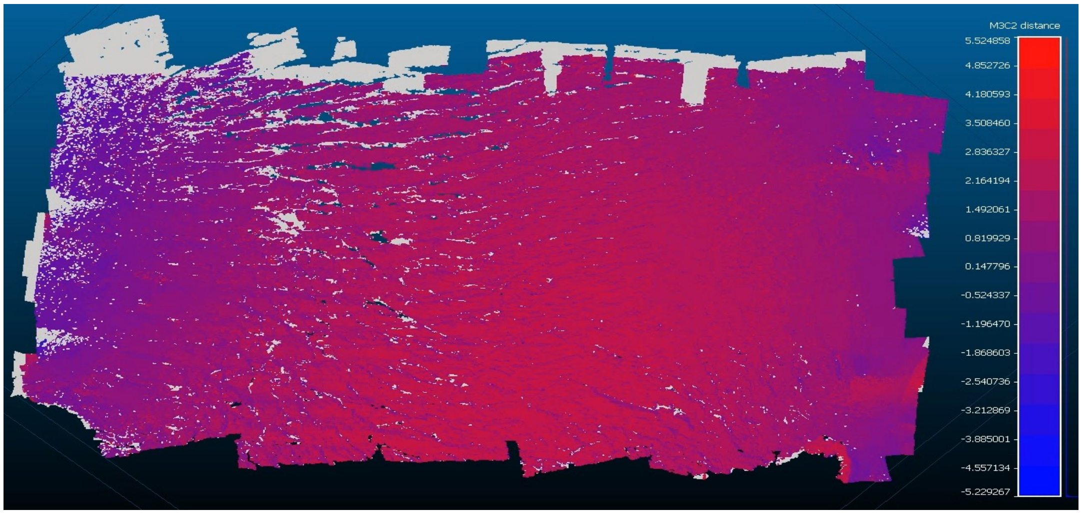


Figure 14. Graphical representation of the M3C2 distance.

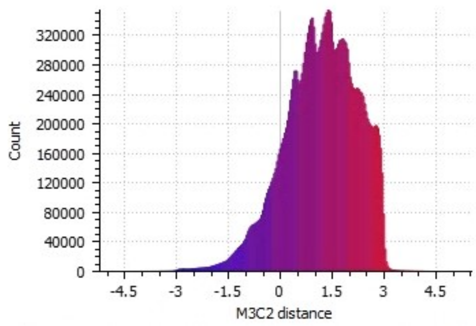


Figure 15. Histogram of the M3C2 distance.

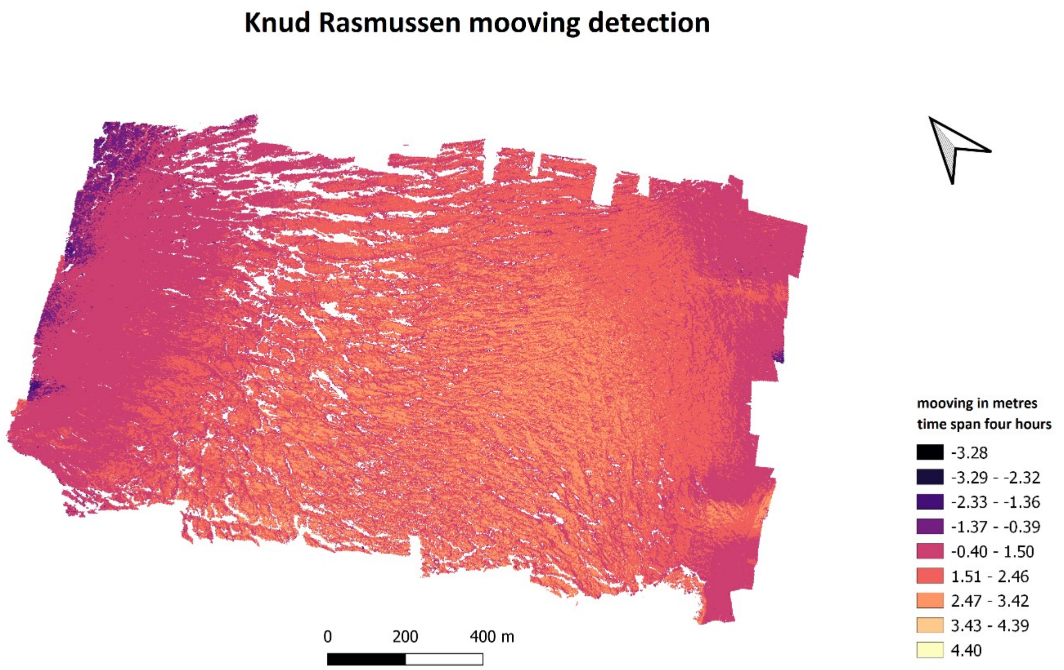


Figure 16. Areas of significant change on the Knud Rasmussen Glacier in the time span four hours.

The results of the analysis show that the glacier moves fastest in the middle, which is not surprising [27]. This result was expected, but it was about defining the average speed of movement of the glacier. From the histogram of M3C2 distances, it can be concluded that (of course, with a certain error up to about 0.7 m) the glacier Knud Rasmussen moves at an average speed probably around 10 m per day. The fastest parts on Wednesday can have a speed over 15 m per day, while the border parts move practically by this method immeasurably in the short time span (Fig.16).

4. Processing of historical aerial images

Thank to Anders Anker Bjørk (Dept. of Geoscience & Natural Resource Management University of Copenhagen) we got a set of historical aerial images from the Danish Greenland expedition (the seventh Thule Expedition 1932-33), (Fig.17).

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 1 December 2020 doi:10.20944/preprints202012.0006.v1

(a)

(b)

Figure 17. (a) The Heinkel seaplane with open cockpit for three persons (pilot, radio-operator and photographer in the back (photo The Arctic Institute, https://arktiskinstitut.dk/). Taking photos was carried out from a height of up to 4500 meters at a temperature of -40 degrees Celsius frequently. Nowadays, these conditions are hardly imaginable, (b) the Fairchild F-8 camera.

The set consist of several oblique aerial images in a form of scanned photo copies. After searching on web, these original images were taken (probably) by the Fairchild F-8 photogrammetric camera, which was released in 1930. Original images were taken probably on a film 5"x7", the focal length was 240mm (12"). We only found this information about the photos. The fiducial marks were very difficult to find and the frame data was unusable. It was uncertain whether the photographs were complete in original format. Fortunately, the centre of the image was highlighted by a puncture and a mark in the photographs. All scanned paper photocopies had to be transformed into detected centres, fitted and cropped according to poorly visible fiducial marks to the same format. Projective transformation was used, which got the best results.

Only eight historical images were selected, from which a project was created to process image information into a 3D model. After many experiments, the project was successfully completed. It was necessary to define at least basic parameters instead of elements of internal orientation. A focal length of 240 mm was used, and the pixel size (14.2 μm) was derived from the size of the scanned photographs and the original image size of 5´´by 5´´ (the additional part on film was used for frame information as time, photo number etc.). Processing the data into a 3D model was difficult and experimental. Metashape software was used. The first attempt at automatic processing was unsuccessful, which was expected. It was necessary to the find suitable tie points manually; in the end, 25 tie points were used for a correct calculation. A sparse cloud was calculated and the points were filtered using gradual selection experimentally, the camera parameters were recalculated until stable results were obtained, which - again only experimentally - were acceptable. The big problem was that the pictures did not have a regular overlap, they were taken by hand and it was almost always a pair of similar pictures. From the flight sequence of images of the Knud Rasmussen glacier, all images were finally processed, but it must be said that the first two images were processed after tens of attempt due a small overlapping. In the end, however, it can be said that we managed to create a relatively good and illustrative model of a historical status (Fig.18-20).

The most interesting result is the fact that the face of the Knud Rasmussen glacier practically changes very little compared to the dramatically receding other glaciers, including right next to the mouth of the Karale glacier (the glacier on the left part of the model).

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 1 December 2020 doi:10.20944/preprints202012.0006.v1

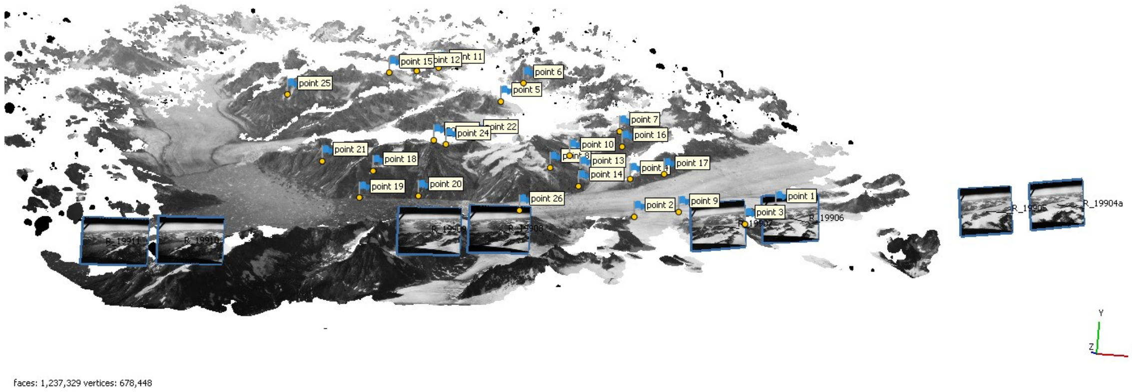


Figure 18. The created 3D model of Karale (left) and Knud Rasmussen glacier mouths (right) with tie points and photo positions; 1.23 million faces.

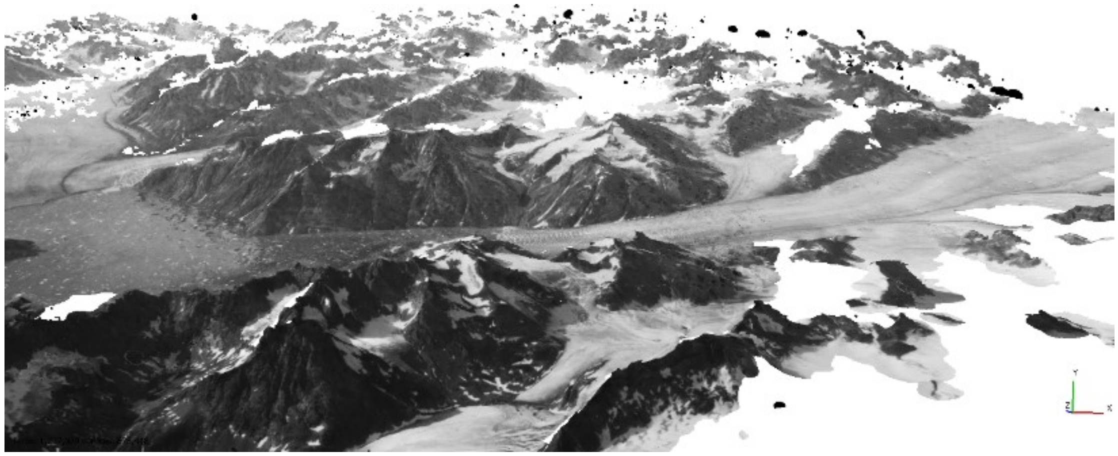
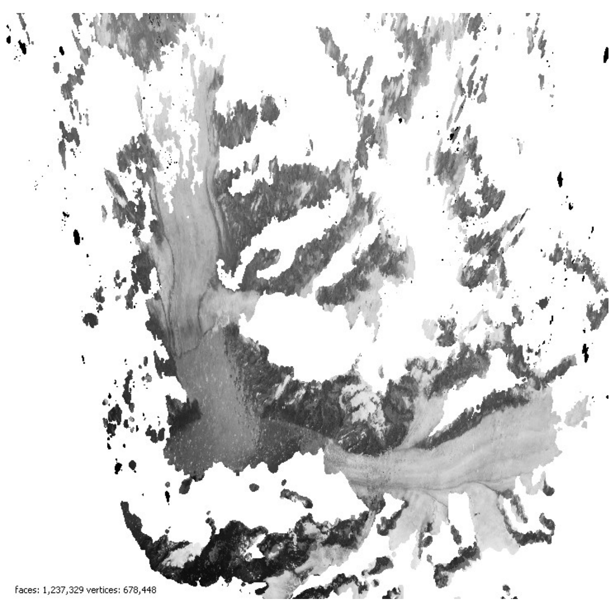


Figure 19. A detail of the 3D model – the Knud Rasmussen glacier in the 1930s.

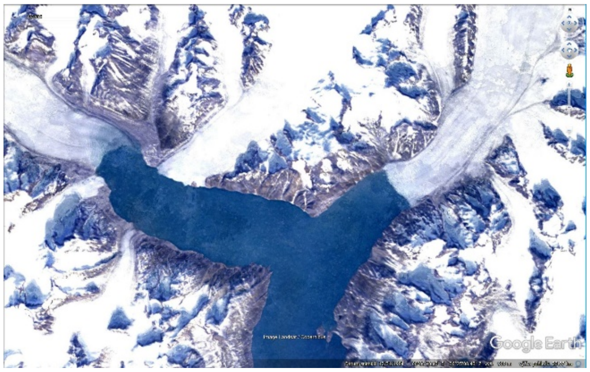


 doi:10.20944/preprints202012.0006.v1

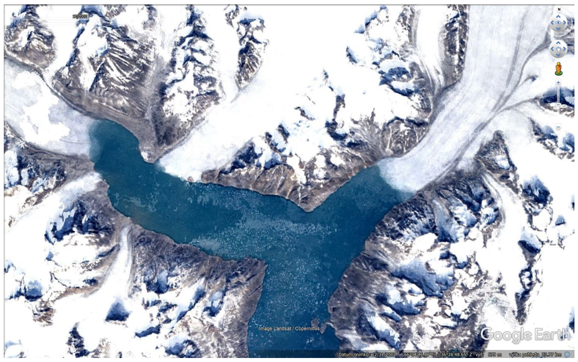
Figure 20. An orthographic view on the 3D model shows glacier faces; it can be joined with satellite and drone images. Unfortunately, the images were taken as oblique which caused a considerable amount of hidden parts due to perspective (white areas).

5. Landsat data

Google Earth provides previews of Landsat satellite data from 1984-2016 (Fig.21) for the Karale and Knud Rasmussen glaciers. The data were always taken on the same day (directly on the last day of the year, Dec 31st), which is an advantage for comparison. In ArcGIS all the images were compared (Fig.22). It can be seen from the series of images that major changes to the front of the Knud Rasmussen glacier did not occur until after 2000. The Karale glacier began to recede as early as 1990.



(a)



(b)

(c)

Figure 21. Landsat data from Google Earth, (a) from 1984, (b) from 2002, (c) from 2016.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 1 December 2020 doi:10.20944/preprints202012.0006.v1

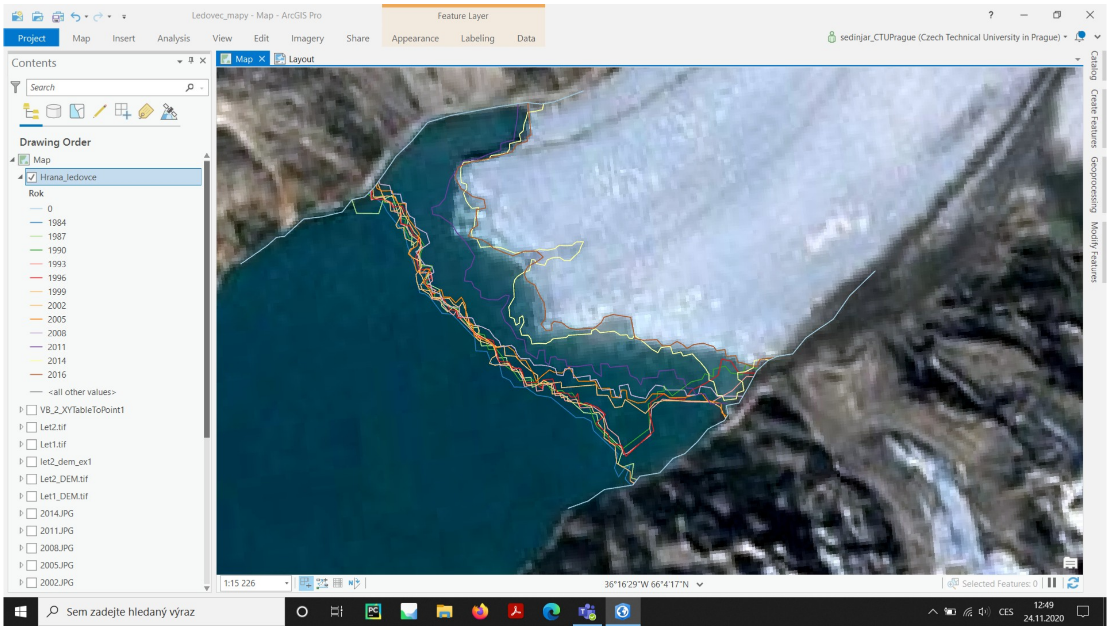


Figure 22. Landsat data from Google Earth, the Knud Rasmussen changes interpretation between 1984-2016 (until 2011 small changes only).

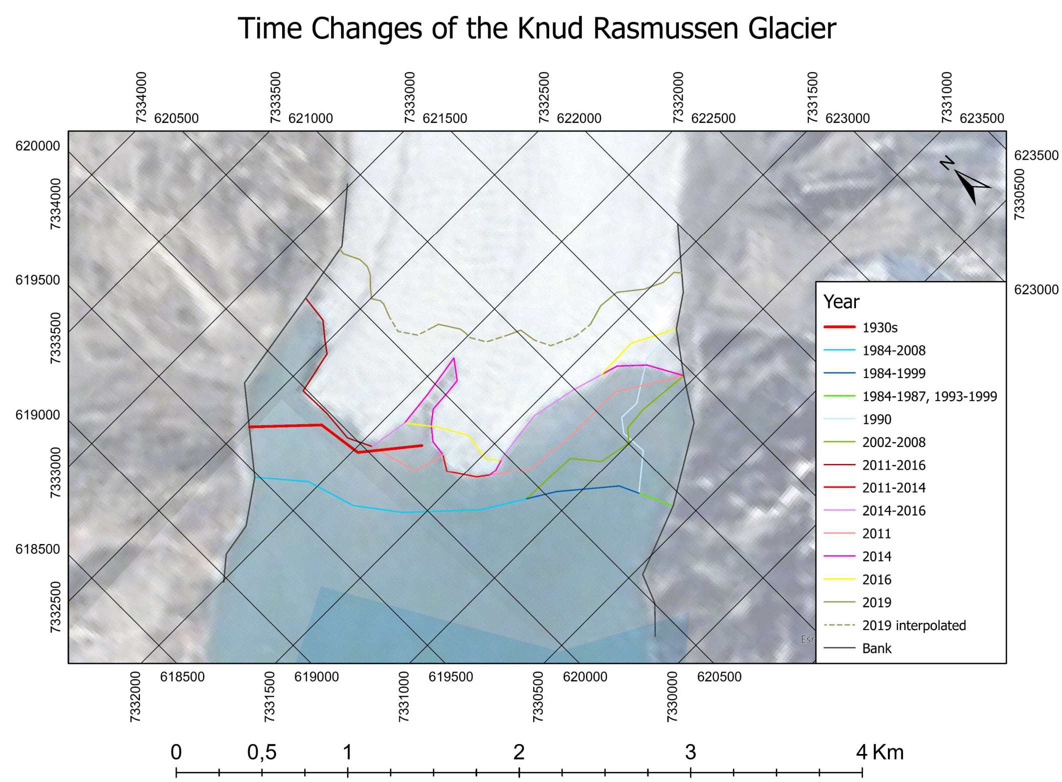


Figure 23. A final interpretation of glacier changes between 1932 and 2019.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 1 December 2020 doi:10.20944/preprints202012.0006.v1

Table 1. The approximate changes of the Knud Rasmussen Glacier; the basic state was the year 1984 - i.e. the state "zero".

Year	Decrease [thousand m²]
1984	0
1932	-200*
1987	+10
1990	-204
1993	+200
1996	-80
1999	-50
2002	-230
2005	-410
2008	-495
2011	-700
2014	-234
2016	-207
2019	-967*

*interpolated, the data did not cover the entire glacier

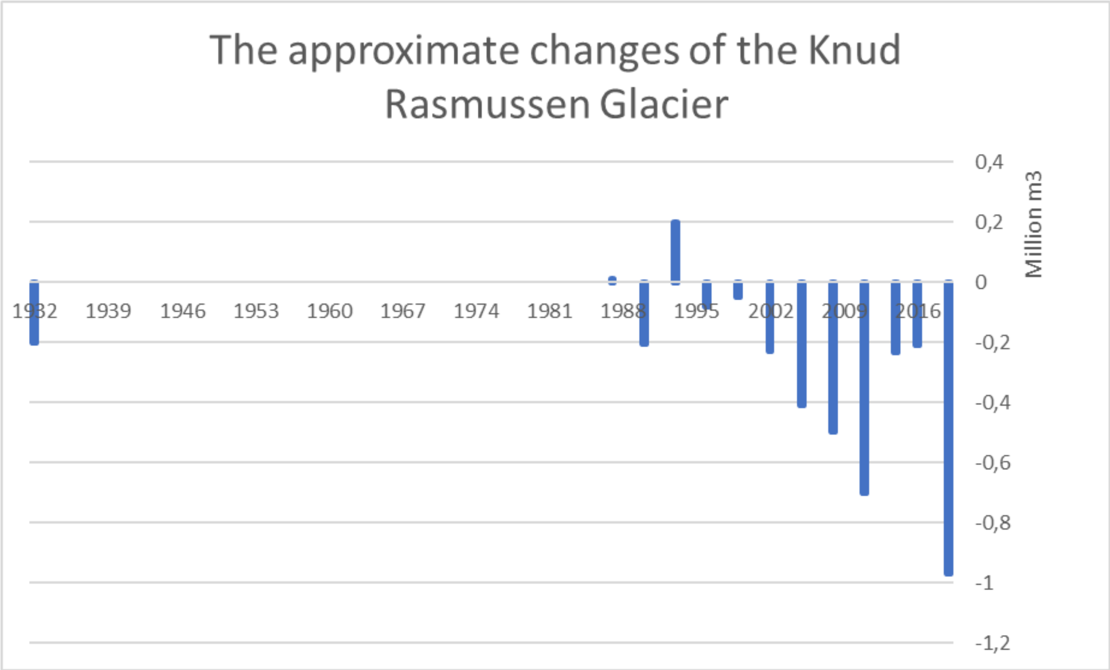


Figure 24. The Knud Rasmussen Glacier changes between 1932 and 2019.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 1 December 2020 doi:10.20944/preprints202012.0006.v1

Figure 25. The Knud Rasmussen Glacier in historical photo (detail); unfortunately, from this photo cannot be possible to get 3D information (only the glacier delimitation).

In the 1930s, the condition of the glacier was the same as in the early new millennium until 2011. This is quite clearly evident from the georeferenced orthophoto from the 1930s. The north-eastern part of the glacier front was located at the position from 2002-2008. The front of the glacier from the 1930s was behind the front from 1984. But we do not know exactly when the flight was made, we know that it was very likely in the Summer. The question is what the front of the glacier looked like in the winter in the 1930s. Similarly, the data from 2019 are from a Summer that was warm (Fig. 23-25). Other satellite dates are always from winter.

5. Discussion and Conclusions

The research looked at the possibility of monitoring the flow rate of the Knud Rasmussen glacier in eastern Greenland using RPAS based on tome changes detected from two overflights. According to the available results, it can be stated that the most significant changes occur in the middle part of the studied area. That was expected. The M3C2 distance histogram shows that the changes rarely exceed three meters. A typical movement of the middle part of this glacier can be between 1,5-2m in a time span 4 hours, it means 9-12m per day, which is acceptable. There is, of course, a possible error of up to RMS 67cm, given the inaccuracy of joining both point clouds. In conclusion, it can be stated that the use of a drone for monitoring the speed of movement of the glacier is possible even after a relatively short time span. Of course, it depends on the type and parameters of the glacier. The fastest running ones have a speed in the middle of up to tens of meters per day (Egi glacier, Jakobshavn glacier, etc., Greenland). In the case of the Knud Rasmussen glacier, the flow rate is considerable and can reach a value of around 12 m per day; however, this is only an extrapolation. It is true that only a short time span was used, and the parameters of the flight were not ideal due to the conditions and time problems. From the historical images, we can deduce that the glacier recedes inland and its flow rate clearly increases, like most other glaciers. It is true that the Knud Rasmussen glacier retreats into the inland not so progressively as by other glaciers, which have moved backward on kilometres to inland due to climate change. An analysis of historical images, satellite images and new drone images shows that the front of the Knud Rasmussen glacier was practically in the same place from the 1930s until 2000. Only later the glacier began to recede. Satellite data on the Google Earth is outdated for the area, with new drone images showing the accelerated retreat of the glacier front in recent years. However, the newest (2019) and the oldest (1932-1933) image data were obtained in the summer, whereas satellite data from Landsat were always acquired on the last day of the year.

Author Contributions: Conceptualization, K.P.; methodology, K.P and K.P. jr.; technical advisory and supervision, K.P. and JŠ.; data processing, K.P., K.P. jr. and J.Š.; investigation, K.P.; writing—original draft preparation, K.P.; writing—review and editing, K.P. jr. and J.Š.; visualization, K.P., K.P. jr. and J.Š.; project administration, K.P.; All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Czech Technical University in Prague Grant number SGS20/053/OHK1/1T/11 and the APC was funded by the Czech Technical University in Prague, FCE, dept. of Geomatics".

Acknowledgments: The project was funded partly by the Faculty of Civil Engineering, CTU in Prague for university-specific research. Finally, we would like to thank Mr. Arved Fuchs and crew member Dagmar Aaen for an incredible experience and perfect service and to Anders Anker Bjørk (University of Copenhagen) for the photographs provided and the immediate and friendly response.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

References

1. Cartographic expeditions to Greenland, (cited 10-11-2020) https://en.wikipedia.org/wiki/Cartographic_expeditions_to_Greenland
2. Pickering, K. (Ed.) Amundsen. *The International Journal of Scientific History*, DIO Vol. 10, **2000**, Triple Issue: Copublished with the University of Cambridge Expansion of DIO Report to N.Y.Times Page One 1996/5/9. http://www.dioi.org/vols/wa0.pdf
3. Běhounek, F. Trosečníci polárního more (Castaways of the polar sea). Albatros, Prague, **1955** (reprint 1989, in Czech)
4. Slater, T.; Hogg, A.E.; Mottram, R. Ice-sheet losses track high-end sea-level rise projections. *Nature Climate Change*, 1–3. **2020**. ISSN 1758-6798. Retrieved 8 September 2020. https://doi.org/10.1038/s41558-020-0893-y Mouginot, J.; Rignot, E; Bjørk, A.A.; Van den Broeke, M.; Millan, R; Morlighem, M; Noël, B; Scheuchl, B; Wood, M. Forty-six years of Greenland Ice Sheet mass balance from 1972 to 2018. Proceedings of the National Academy of Sciences. **2019**, 116 (19) 9239-9244; https://doi.org/10.1073/pnas.1904242116, https://www.pnas.org/content/116/19/9239
5. Encyclopædia Britannica. 1999 Multimedia edition, (cited 28-10-2020)
6. Greenland Rapidly Rising as Ice Melt Continues, **2020**. www.miami.edu [online], (cited 2020-10-05), http://www.miami.edu/index.php/news/releases/greenland_rapidly_rising_as_ice_melt_continues/
7. Houghton, J.E.T; Ding, Y.; Griggs, D.J.; Noguer, M.; van der Linden, P.J.; Dai, X.; Maskell, K.; Johnson, C.A. (eds.), Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), **2001**. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 881pp. Archived from the original on 2006-02-10. https://www.researchgate.net/publication/216811760_Climate_Change_2001_The_Scientific_Basis
8. Sasgen, I.; Wouters, B.; Gardner, A.S.; King, M. D.; Tedesco, M.; Landerer, F.W.; Dahle, Ch.; Save, H.; Fettweis, X. Return to rapid ice loss in Greenland and record loss in 2019 detected by the GRACE-FO satellites. **2020**. Communications Earth & Environment. **1** (1): 1–8.. ISSN 2662-4435. Retrieved 6 September 2020. https://doi.org/10.1038/s43247-020-0010-1
9. Fridtjof Wedel-Jarlsberg Nansen, https://en.wikipedia.org/wiki/Fridtjof_Nansen, (cited 10-10-2020)
10. Knud Rasmussen. https://alchetron.com/Knud-Rasmussen, (cited 10-10-2020)
11. Andrej Abplanalp, Swiss National Museum, Alfred de Quervain, https://blog.nationalmuseum.ch/en/2020/02/de-quervain-greenland-1912/ (cited 10-10-2020)
12. Stephan Orth. Opas Eisberg. *Auf Spurensuche durch Grönland*. Spiegel Online. **2013,** pp.251
13. Bjørk, A.A.; Kjær, K.H.; Larsen, N.K.; Kjeldsen, K.K.; Khan, S.A.; Funder, S.V.; Korsgaard, N.J. *The Greenland Ice Sheet - 80 years of climate change seen from the air*. Natural History Museum of Denmark, Faculty of Science, University of Copenhagen, **2014**. 978-87-87519-46-5. 180pp.
14. Bjørk, A.A, Kjær, K., Korsgaard, N. et al. An aerial view of 80 years of climate-related glacier fluctuations in southeast Greenland. *Nature Geoscience*, 5**,** 427–432. **2012**. https://doi.org/10.1038/ngeo1481

 doi:10.20944/preprints202012.0006.v1

15. Raeva, P.; Pavelka jr, K.; Geospatial and temporal analyses of rural area for vegetation analysis. *Civil Engineering Journal*; Prague Iss. 2, **2020**. https://doi.org/10.14311/CEJ.2020.02.0021
16. Šedina, J.; Housarová, E.; Raeva, P. Using RPAS for the detection of archaeological objects using multispectral and thermal imaging. *European Journal of Remote Sensing*. **2019**, 52(sup1), 182-191. ISSN 2279-7254. https://doi.org/10.1080/22797254.2018.1562848
17. Korth, W.; Hoffman, U.; Hitziger, T.; Küchenmeister, T., Pawelka, K. Klimabedingte Veränderungen des Inlandeises im südlichen Grönland, 19. Internationale Geodätische Woche Obergurgl. **2017**. Berlin and Offenbach: Herbert Wichmann Verlag, Wichmann Verlag. ISBN 978-3-87907-624-6.
18. Näcke, L., Vergleich kinematischer GNSS-Daten aus Ostgrönland (Comparison of kinematic GNSS data from East Greenland), BTU Cottbus, Germany, Bachelor Thesis, **2020**
19. Pavelka, K.; Šedina, J.; Matoušková, E.; Hlaváčová, I.; Korth, W. Examples of different techniques for glaciers motion monitoring using InSAR and RPAS. *European Journal of Remote Sensing*. **2019**, 52(1), 219-232. ISSN 2279-7254. https://doi.org/10.1080/22797254.2018.1559001
20. Bash, E.A.; Moorman, B.J.; Gunther, A. Detecting Short-Term Surface Melt on an Arctic Glacier Using UAV Surveys. *Remote Sensing*. 2018, 10, 1547. https://www.mdpi.com/2072-4292/10/10/1547#
21. Zwally, J., Abdalati W., Herring,T.,Larson, K.,Saba,J., Steffen, K. Surface Melt-Induced Acceleration of Greenland Ice-Sheet Flow Science. **2002**. 297 (5579): 218–222. https://doi.org/10.1126/science.1072708
22. Štroner, M., Pavelka, K. Lineární prostorová transformace (Linear spatial transformation). In Czech. *Geodetický a kartografický obzor*. **2001**, Vol. 47, Nr. 3, p. 233-235. ISSN 0016-7096.
23. M3C2 (plugin). CloudCompare. (cited 10-10-2020) https://www.cloudcompare.org/doc/wiki/index.php?title=M3C2
24. Lague, D.; Brodu, N.; Leroux, J. Accurate 3D comparison of complex topography with terrestrial laser scanner: Application to the Rangitikei canyon (N-Z). ISPRS Journal of Photogrammetry and Remote Sensing. 82. **2013**. https://doi.org/10.1016/j.isprsjprs.2013.04.009
25. Barnhart, T.B.; Crosby, B.T. Comparing Two Methods of Surface Change Detection on an Evolving Thermokarst Using High-Temporal-Frequency Terrestrial Laser Scanning, Selawik River, Alaska. Remote Sensing. **2013**, 5, 2813-2837. https://www.mdpi.com/2072-4292/5/6/2813#
26. The Greenland Ice Sheet 80 years of Climate change seen from the Air, (cited 20-10-2020), https://www.youtube.com/watch?v=ygCKQZiOSNw